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THE MODE OF FORMATION OF CERTAIN GNEISSES IN THE HIGHLANDS OF NEW JERSEY

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PART I. OBSERVATION OF FIELD PHENOMENA

In Northwestern New Jersey a broad belt of pre-Cambrian crystalline rocks extends across the state and is prolonged northeasterly into New York, forming there the Highlands of the Hudson. On the southwestern side it is continued into Pennsylvania. The rocks which compose this belt are of considerable variety. Gneissic rocks of several types predominate, but beds of crystalline limestone are associated with them, and masses of rock of granitic and dioritic character, showing at times almost no foliation, are also present. The general trend is northeast and southwest, with steep dips, usually toward the southeast.

The geological character of the region as a whole and of various portions of it has been frequently described. As in other areas of similar foliated gneisses in various parts of the world, the question of origin of the various types has been a most puzzling one. Certain observers have held them to be highly metamorphosed sediments; others have favored the view that they represent the partial differentiation of a still fluid magma, which by continued movement has pressed out the differentiated portions into broad sheets; and a third view would attribute their structure to the shearing and recrystallization of an already solidified mass.

In a number of visits which the writer has made to various portions of the area, certain features have been observed in several places which were believed to be of considerable significance in the interpretation of the mode of origin of the rocks in which they occurred, and during the past summer (1913) especially favorable conditions for observation were found at a quarry which is being newly opened up at Pompton Junction. The quarrying operations and the stripping-off of the soil from a large area have disclosed the structural features in a very plain manner, and the relations thus revealed afford evidence toward an explanation of the processes by which the structures of the rock in question have originated. In this article it is proposed to give some description of the features found in this locality and to present the evidence regarding the mode of origin which they suggest. It has seemed desirable also to consider certain of the general properties of magmas with the purpose of finding an explanation for some of the phenomena observed in the field. It is believed that rock-types of a similar character are to be found in other portions of the area and indicate a similar origin, but at the same time it is recognized that the region as a whole is most complex and that this description and explanation do not apply to all parts of it.

In recent publications of the United States Geological Survey, W. S. Bayley and A. C. Spencer[1] have described in somewhat general terms certain features of the gneisses in a manner which indicates that a theory of origin similar in some respects to that which will be presented here was held in view, and others[2] appear to have favored similar explanations. Thus far, however, descriptions of the mode of action of the processes concerned, as illustrated by the resultant rock structures, and a discussion of the conditions under which they operated, appear to be lacking.

The quarry in question is that of the Pompton Pink Granite Company,[3] and is situated at the intersection of the New York, Susquehanna & Western Railroad and the Greenwood Lake Branch of the Erie Railroad, near the southeastern front of the Highlands.

A number of years ago a quarry was in operation at this point and a considerable amount of granite for building-purposes was obtained from it. The dressed stone was of a very pleasing appearance and was quite widely used, but difficulty was found in obtaining large blocks free from streaks and bands of dark-colored minerals. This objectionable feature probably led to the abandonment of the workings. Recently another company has taken hold of the property and without attempting to do much work at the old site they have gone several hundred feet up the ridge, at the base of which the old quarry lies, and have exposed great masses of granite of the same composition as before, nearly free from inclusions. Extensive operations are now being undertaken at this point.

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[1] W. S. Bayley and A. C. Spencer, *Franklin Furnace Folio* (1908), and *Passaic Folio* (1908).

[2] J. V. Lewis, *Annual Report of the State Geologist of New Jersey for 1908*, p. 64.

[3] I wish to express my appreciation of the courtesy of the general manager of the company, Mr. Charles H. McIntyre, for the opportunity which was afforded to visit the quarry workings and all parts of the property.

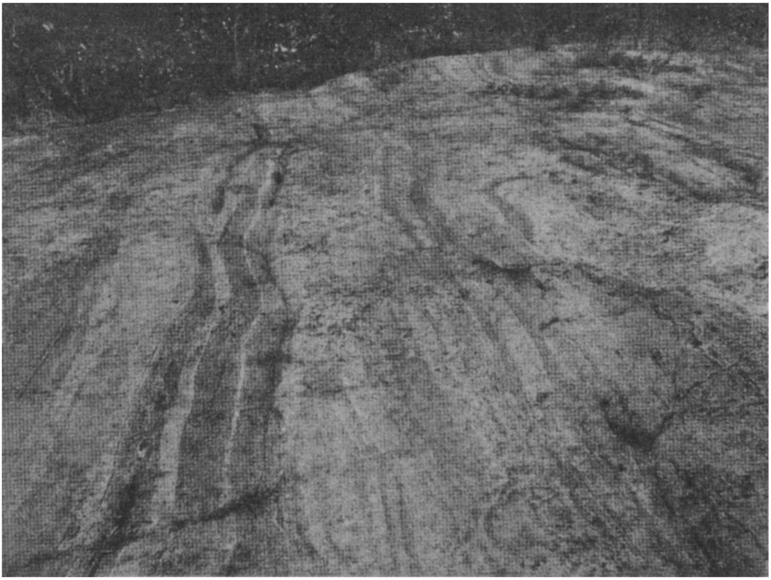

FIG. 1

In the *Annual Report of the State Geologist of New Jersey for 1908*, in an article on the building-stones of the state, J. V. Lewis gives an excellent description of the macroscopic and microscopic characteristics of the rock and some information regarding the field relations. It is evident that he recognized the intrusive nature of the granite into the gneisses of the region, but he does not enter into any extended description of the details and results of the process.

At the quarry itself and in the immediate vicinity two rock types are found, differing greatly from each other structurally.

The first is a very coarse-grained granite, almost a pegmatite in texture, in which crystals of microcline, or crystalline aggregates of the same mineral, occasionally attain a diameter of four or five inches. Where found in the largest masses it is almost free from dark minerals and consists essentially of quartz and two kinds of feldspar. In such places it is very massive and shows little or no indication of parallelism in the disposition of its constituent minerals. At the other extreme from this type is a finely banded gneiss, such as is shown in Fig. 1. This photograph was taken at an exposure of a large surface of glaciated rock about one-fourth mile (0.4 kilometer) north of the quarry, and the relations shown are typical of much of the rock in the vicinity. The light bands consist principally of quartz and feldspar, while the dark bands and streaks are characterized especially by large amounts of biotite, hornblende, or chlorite mixed with the quartz and feldspar. When developed in the manner shown in this photograph, either the dark or the light bands may individually have any thickness up

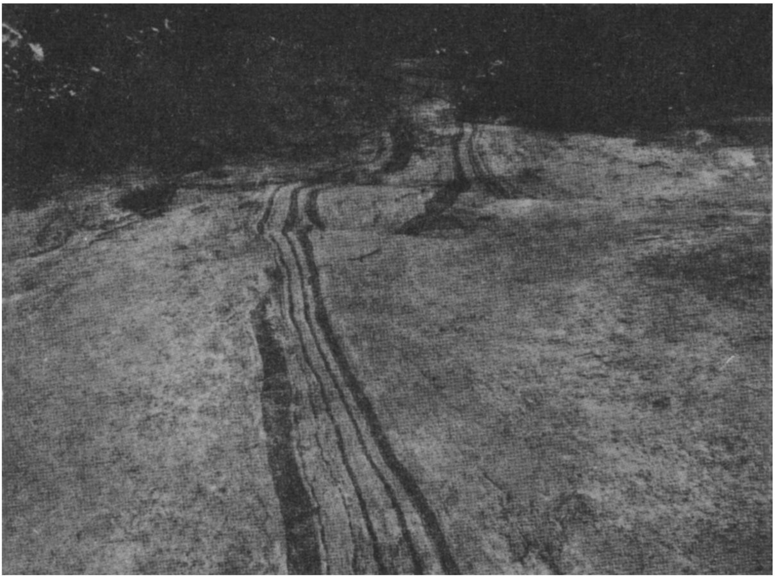

FIG. 2

to several inches, and show remarkable continuity and parallelism. The relations shown at this point, however, are by no means universal. It is found frequently that the lighter bands swell and pinch in an irregular manner and that the darker bands are interrupted or fade out in places and may be continued after an interval. By a further development of such features and by an increasing predominance of the light-colored bands, we arrive at such results as are shown in Figs. 2 and 3. These views show another portion of the glaciated surface at the same locality as Fig. 1 and represent dark bands separated by the light-colored granitic rock and bordered on both sides by large masses of granite. These two photographs illustrate very well the persistence and continuity sometimes shown by the bands of basic rock through masses of granite, and also the manner in which they may suddenly lose their identity and fade out within a few feet or inches. Fig. 4 is a sketch of the details at the termination of one of the bands of Fig. 3. Fig. 5 shows somewhat similar features.

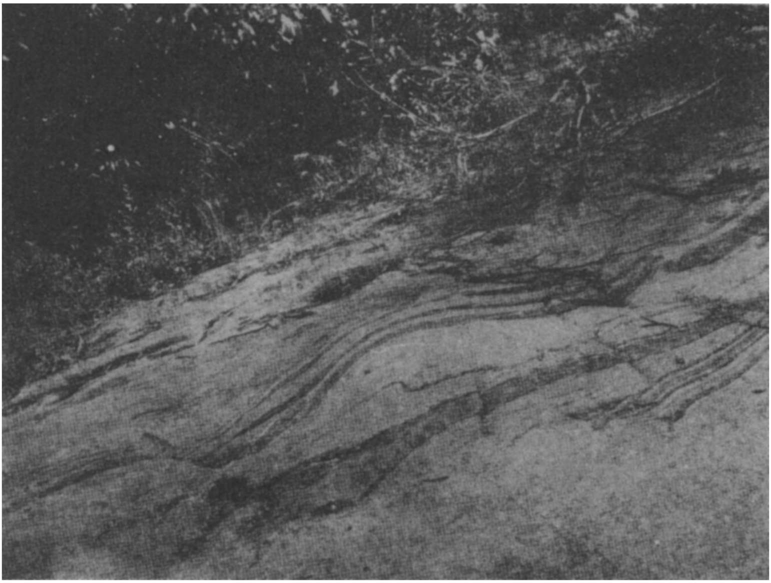

FIG. 3

Microscopic examination of thin sections of the various types shows that the purest granite is made up almost entirely of microcline (having always a little microperthitic intergrowth) an acid plagioclase very near albite, and quartz. In such a type dark minerals may be almost lacking but when present they consist of aggregates of chlorite and epidote whose character bears evidence of a derivation from original biotite. Indications of a slight amount of deformation are often shown by strain shadows in the quartz and the curving of twinning lamellae in the feldspars, and in some cases this has gone so far as to produce cracks, along which epidote, chlorite, quartz, and calcite have been deposited. It is very evident, however, that nothing resembling granulation or mashing has occurred. In the darker bands the distinctive feature is the large amount of biotite or hornblende present. In addition quartz is an important constituent, as well as microcline and acid plagioclase. Magnetite is also quite common, together with such secondary products as chlorite, epidote, and sericite in rather minor

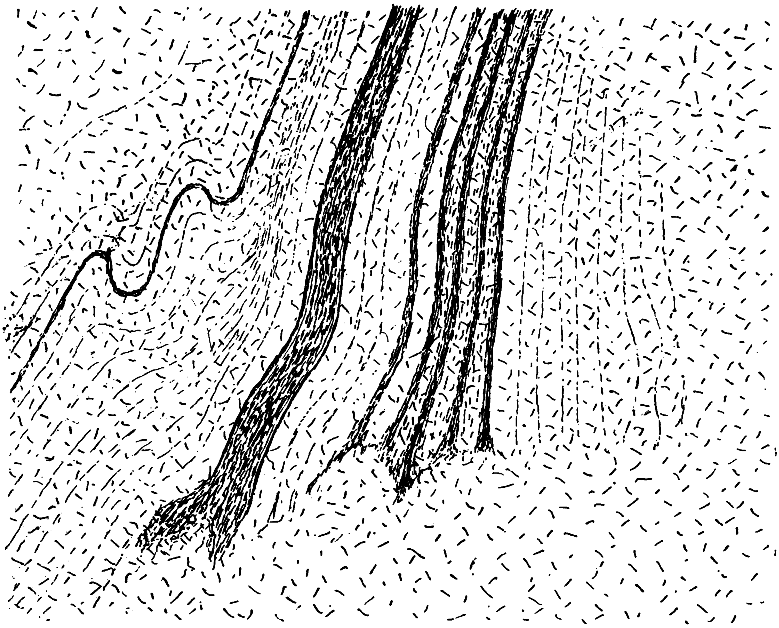

FIG. 4

amount. As in the massive granite, some indications of strain and deformation are apparent, but evidences of granulation to any important degree are lacking.

At the old quarry and at natural exposures in the neighborhood the rock masses exhibit features similar to those which have been described. Fig. 6 shows a portion of a glaciated surface adjacent to the old workings. The bands appearing in the foreground are composed of very dark hornblende-biotite gneiss, having a collective width of 2–3 feet, which are exposed for a length of about 25 feet and are cut off at both ends by granite. At their terminations the individual layers become considerably separated by an increase in the width of the dividing bands of granite. This is a feature which was noted in a number of instances. At each side there are large masses of coarse granite in which traces of dark minerals arranged in parallel lines are just visible.

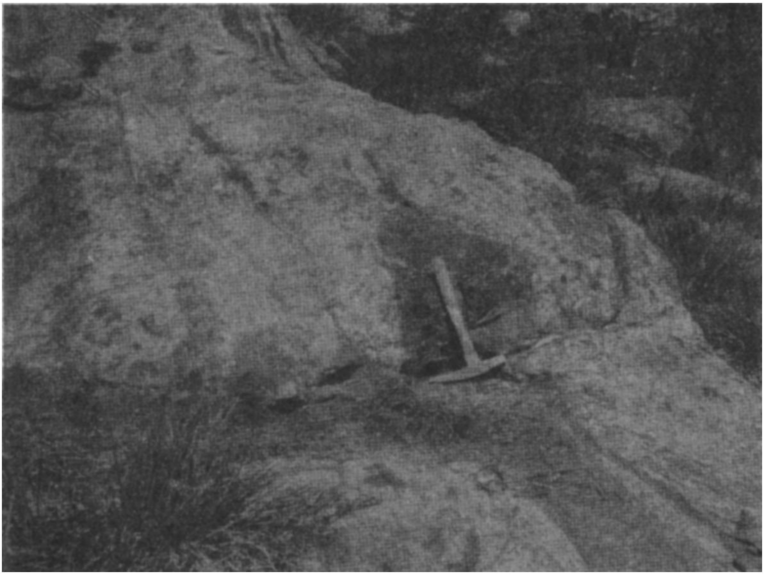

FIG. 5

In the old quarry, where dark inclusions are fairly plentiful, the quarry-faces, which are still perfectly fresh and clean, exhibit the finer details of the relations between the granite and the basic streaks more plainly than do natural surfaces. Figs. 7–11 represent such exposures. In the vicinity of the quarries the coarsely granitic material is far in excess of the banded rock, but occasionally the latter is very plentiful, especially in the older opening. In places there is probably as much of the finely foliated rock as of the massive material; in other places there are great masses of granite almost free from inclusions (Fig. 12). Between these two extremes there are all degrees of transition in relative proportions of the two. Quite frequently the contact between granite and inclusions is sharp, although the minerals at the border always interlock; elsewhere the minerals characteristic of the inclusion become more and more infrequent at the sides until only faint parallel lines can be seen in the granite. The manner of transition shows several interesting features. It appears in some cases that the basic minerals at the immediate contact have become involved in the granitic magma without losing their identity or parallelism, so that a perfect

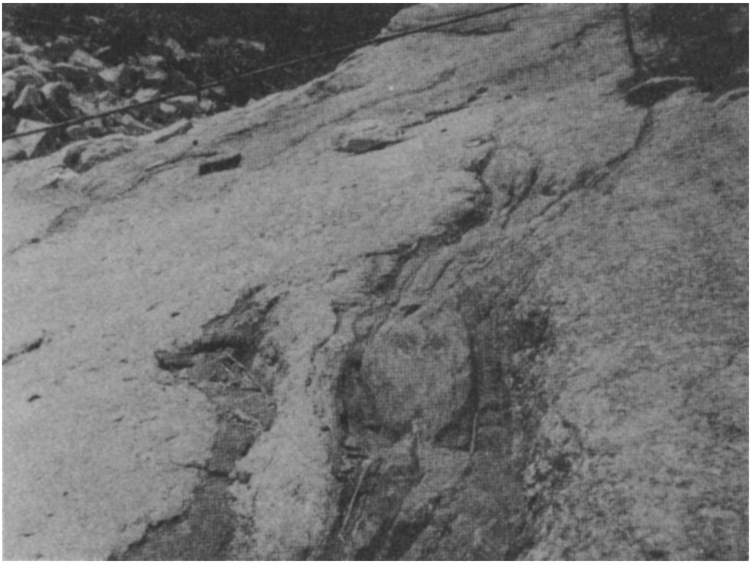

FIG. 6

transition is produced from the hornblendic or biotitic gneiss or schist, in which foliation is prominent, through gradations in which the dark minerals become less and less noticeable and the proportion of granite increases, up to a type in which little or no parallelism of structure can be perceived. In other places the dark minerals appear to have been taken up or digested by the magma and to have crystallized out again in large blades. Even in the latter case it is not always certain that perfect solution has been effected at any one time. The process may have been rather in the nature of a chemical reaction with the original minerals or the solution and redeposition of a portion of the material at a time, leaving the general relations undisturbed. This possibility is

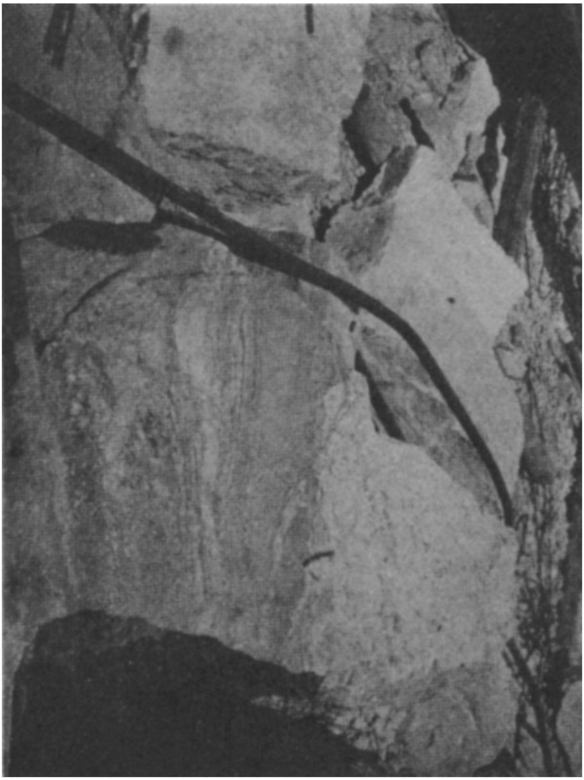

FIG. 7

suggested by the fact that frequently even the coarser micaceous blades or aggregates of dark minerals show evidence of parallelism, and this would be difficult to account for under the supposition that solution was so perfect that the original structure was completely wiped out. In Fig. 9 some of these features may be seen. The band of dark inclusions appearing in the middle of the quarry-face has a boundary with the granite on the left-hand side which is quite sharply defined and persistent. On the right there is more scattering of the dark minerals and an irregular, ill-defined marginal portion. Still farther to the right the original bands have been pretty well replaced by coarse granite and show only as scarcely traceable lines of coarse mica or chlorite. The block shown in Fig. 11 would by itself be considered a fairly normal massive granite, but even here a suggestion of parallel arrangement of the dark minerals may be perceived, surviving as a slight evidence of the process by which it has been produced. Frequently, however, in the largest masses of granite all indications of a parallel structure are absent.

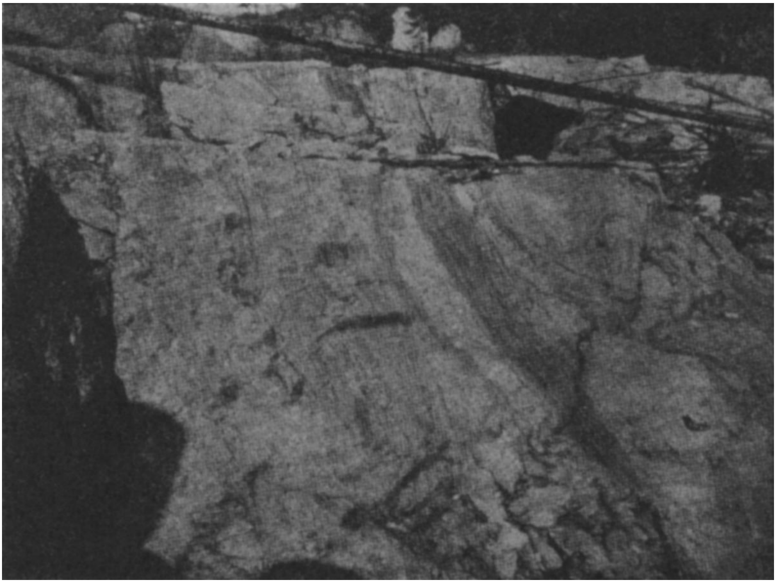

FIG. 8

It was observed in many instances that in such occurrences as show bands of basic rock in largest amount the adjacent granite contains the greatest quantity of dark silicates, and where inclusions are rare the granite is very light colored and nearly free from ferromagnesian minerals, and it seems probable that the invading magma was composed essentially of quartz and feldspars, and that the dark minerals, even in massive granite, were derived to a large degree from the rocks which were invaded.

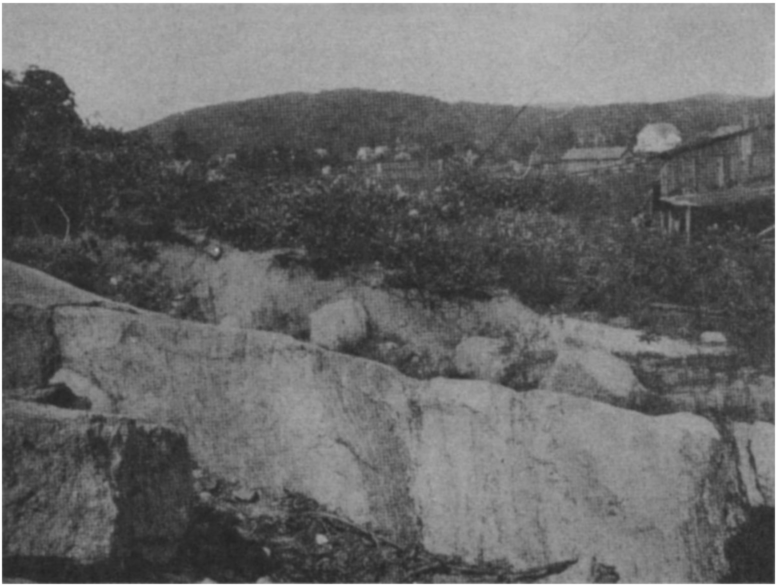

FIG. 9

In the foliated gneisses the light bands are frequently of the same composition and appearance as the granite of the large masses, and their relations to such bodies and their general characteristics are such as to point strongly to their being essentially portions of the same magma which have traveled long distances along parallel layers of inclosing rock. The mechanism of injection appears to have involved a progressive movement of a rather thin magma between the layers of a foliated rock, in some cases spreading them apart by the force of injection, elsewhere being transfused into the original layers and crystallizing these, or digesting and carrying away certain constituents, or entering into reactions with the component minerals. The variations found may be readily explained by the greater predominance of one or the other of these factors. The manner of action will be considered in more detail in Part II of this article. The fluidity of the magma is manifested by the narrowness and persistence of some of the injected layers. The question of the actual degree of fluidity will also be considered in the later discussion.

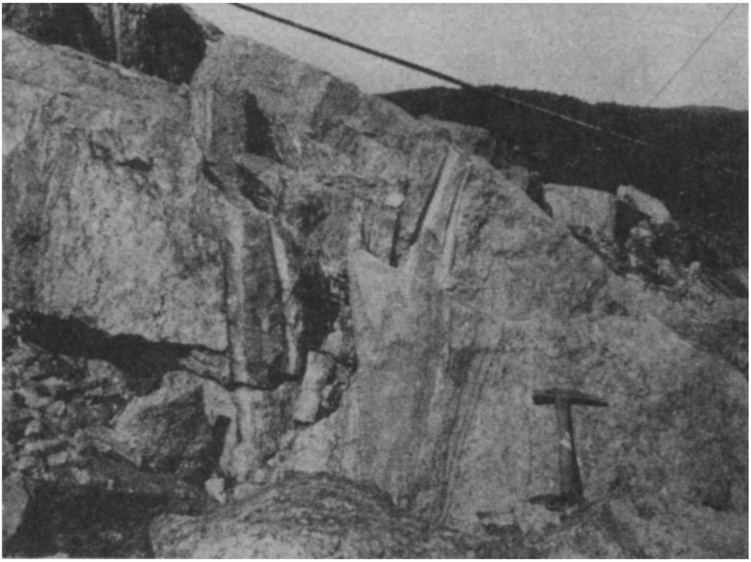

FIG. 10

Certain phenomena suggest that a force of crystallization may at times have been an effective factor in separating the layers. Aggregates of microcline and quartz crystals in the form of augen are seen, inclosed by curving bands of schist as in Fig. 13. Such augen may have suffered a small amount of deformation and granulation of the solid material by shearing movements subsequent to crystallization, but obviously not to such a degree as to drag out the crushed fragments into a band, as has occurred in some augen-gneisses.

Inasmuch as quarrying operations have exposed the rock masses in three dimensions, it is possible to arrive at a very clear conception of the form of the gneissic inclusions. It is seen that they dip very steeply and have an extension in depth comparable to their prolongation along the strike. Their form is therefore that of thinly tabular sheets.

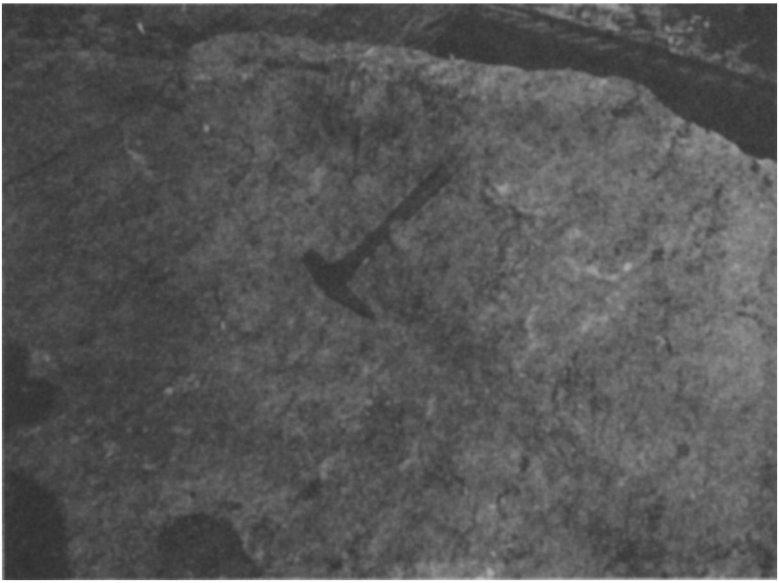

FIG. 11

In general the strike of the bands is almost straight and conforms to the general northeast-southwest strike of the region, but in places the layers are more or less curved and occasionally so much contorted as to suggest a "kneading" of the material. In Fig. 10 one of the abrupt bends which are often visible is depicted. The movements in the magma by which such features were produced may perhaps be ascribed to the antagonism of forces brought into play by the up-welling of liquid magma into strata subjected to a tangential compression due to the weight of overlying rock. In all cases, however, the appearance of the contorted strata was such as to imply that the flexures were of a minor order, not involving large masses of rock but suggesting considerable freedom of movement among the component layers. The contortions appear to have originated during the period of injection and not during subsequent movements of solidified rock. Frequently individual bands are sharply bent, while others lying at either side, but separated by intervening granite, are nearly straight. An instance of this may be seen in Fig. 3. On the whole the general parallelism of the basic bands lying in the midst of masses of granite and the agreement of their strike with the general strike of the region was a noticeable feature and was considered important in its implication regarding the mechanism of the process by which the granite was injected. It implies that the granitic magma entered among the layers of a previously schistose or foliated rock without causing great disturbance in their position. Some of the layers appear to have become incorporated in the magma, others were forced

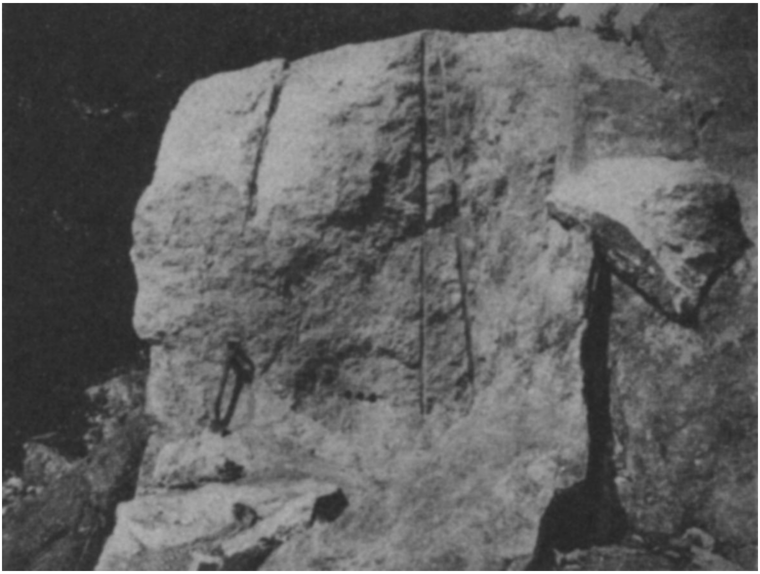

FIG. 12

apart and even sharply contorted in minor folds, but brecciation, or large disturbances of any sort appear to have been lacking. Where the invading magma entered in large quantity, movements of considerable amount within its mass appear to have occurred. One body having a width of nearly 200 feet was observed, in which the infrequent inclusions had a somewhat more blocklike form than in general and a variable strike, approaching at times a right angle to that which generally prevails, implying differential movements within this large mass of liquid. The dark bands shown in Fig. 14 lie somewhat to the northeast of this main mass of granite and trend directly toward it, and are bordered on either side by tongues or offshoots from it. As they approach the granite mass in their prolongation beyond the lower left-hand side of the photograph they curve much more toward the left and are finally cut off or dissolved by the granite.

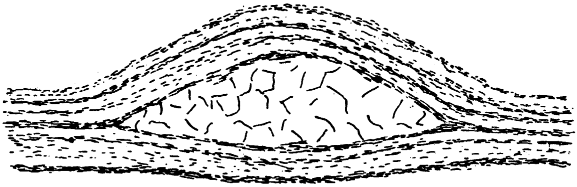

FIG. 13

In the process of igneous intrusion illustrated at this locality it is quite certain that nothing in the nature of "stoping" was a factor of importance. It is not intended to imply, however, that such a process may not have been the effective means of intrusion in other instances. It is assuredly true that in different localities and under varying conditions the mechanics of intrusion have been radically unlike.

Several of the features which have been described argue against the probability that the dark bands represent squeezed-out differentiates in a mass of magma. Probably the most impressive evidence in this connection is the sudden termination of certain sharply defined bands, with indications of corrosion at the end, which was frequently observed. The same phenomenon is opposed to the idea that the elongated structure of the bands of schist is essentially due to a plastic flow. Certain features of rupturing likewise suggest that the attributes of a rigid body were retained to some degree in such cases. Elsewhere, however, the phenomena are more consistent with the idea of softening. The abrupt flexures and general appearance of kneading of the material, as well as the manner in which certain bands gradually fade out along the strike, imply a partial fusion of the original material or a penetration of the magmatic liquor among the grains to such a degree that their mutual adhesion was diminished and some freedom of movement thus permitted.

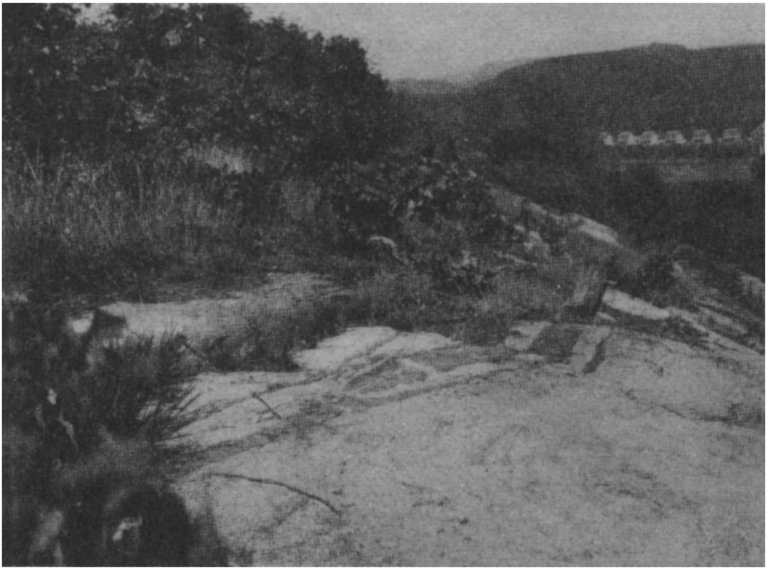

FIG. 14

There can be little doubt that during the period of intrusion the masses of rock now exposed were buried within the crust of the earth to a depth at which the increase of temperature due to the rise of the geotherms was considerable. In seeking an explanation of the phenomena of intrusion the question arises whether the conception which Sederholm[1] has advocated to account for the relations

[1] J. J. Sederholm, *Bulletin de la Commis. Géol. de Finlande No. 23* (1907).

observed in certain areas of pre-Cambrian rocks of Fenno-Scandia may be applicable. He urges that in certain cases the strata have been buried to such a depth that the rocks as a whole have become plastic, and the more fusible portions have actually formed a magma at the horizon observed or at a comparatively small depth below. We are hardly warranted from the evidence at hand in accepting this explanation here. The general parallelism and straightness of the bands indicate that prior to the injection of magma the dominant characteristic of the rock was fissility rather than plasticity. The phenomena of softening must therefore be attributed to the injection itself, but the evidence shows that while the magma was still in movement softening had ensued, and we are led to conclude that the process of injection was long continued. It appears, however, that in the New Jersey Highlands large areas show evidences of granitic injection of the type which has been described, suggesting that beneath such areas the conditions necessary for the softening and flow of masses of rock may have been realized.

The process by which the granite and gneisses have assumed the relations described in the foregoing pages appears to be similar in many respects to that which French geologists, notably Michel-Lévy and Lacroix,[1] have termed *lit-par-lit* injection. In their typical examples the phenomena are attendant upon the intrusion of batholiths of igneous rock into areas of Paleozoic sediments, and the contact phenomena may be plainly seen. In the New Jersey example the appearances imply rather the presence of a reservoir of magma at some lower level, from which offshoots in large and small apophyses were injected into the roof and are now exposed for observation. In many respects, however, the mode of injection appears so similar that the same term may be applied.

It will readily be seen that the resultant gneisses are believed to be composite rocks, made up of material of different sorts, derived from different sources. An older, sheared or bedded rock is postulated, to which magmatic material has been contributed; first, by injection along parallel layers, and second, by a process of absorption exerted by the original rock upon the injected magma. The latter process will be discussed a little later.

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[1] The publications of these two authors which bear upon the subject are quite numerous. Special mention may be made of Michel-Lévy's *Bull. No. 36, Carte géol. fran.* (1893), and Lacroix's *Bull. No. 64* (1898) and *Bull. No. 71* (1900), *Carte géol. fran.*

The nature of the original rock does not appear at all certain. The laminated character might as well be considered as representing bedding planes in a sedimentary series or shear planes in a schist of either sedimentary or igneous origin. The prevalence of ferromagnesian minerals in many of the bands might be supposed to imply a derivation from a basic igneous rock, but there is a question as to how far the present composition represents that of the original material. The French geologists mentioned have directed special attention to the profound changes wrought in the composition of the original sediments by "imbibition" of material derived from the igneous mass. Sederholm also has described similar phenomena accompanying the process of granitization, and the work of Adams and Barlow[1] in the Haliburton and Bancroft areas of Ontario is of great importance in this connection. The last-named geologists present evidence of the metamorphism over large areas of the pure, non-magnesian limestones of the Hastings-Grenville series into amphibolites and pyroxene-gneisses by transfusion of material from invading batholiths of granite.

There is some evidence not far distant from the quarries described that not all of the original rocks of the region could have been of a basic igneous character. About two miles (3¼ kilometers) to the north, a little west of the railway station at Haskell, a bed of crystalline limestone or dolomite occurs in the gneissic series. The thickness is somewhat uncertain but appears to be 20 feet or more. In places the amount of carbonate minerals is large, though tremolite, phlogopite, and a pale-green pyroxene are extensively developed, as well as secondary serpentine. Elsewhere along the same belt carbonates appear to be wholly absent and the rock consists almost entirely of the greenish pyroxene or a mixture of pyroxene and quartz. The belt can be traced by occasional outcrops for several hundred feet. In one place a gneiss composed of feldspar, quartz, biotite, and much garnet occupies a position either on the strike of the limestone or closely adjacent. The strike of the limestone bed is parallel to that of the associated gneisses—an indication that part at least of the foliation is to be attributed to an original bedding. The manner in which minerals from the magma may have been introduced into the limestone and other sedimentary beds will be considered in the discussion which follows.

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[1] Adams and Barlow, "Geology of the Haliburton and Bancroft Areas," *Memoir No. 6, Canadian Geological Survey* (1910); see especially pp. 87 and 157.

[*To be continued*]